$\Delta\Delta$ Excitation in Proton-Proton Induced $\pi^0\pi^0$ Production

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Exclusive measurements of the $pp \to pp\pi^0\pi^0$ reaction have been performed at CELSIUS/WASA at energies from threshold up to $T_p = 1.3$ GeV. Total and differential cross sections have been obtained. Here we concentrate on energies $T_p \geq 1$ GeV, where the $\Delta\Delta$ excitation becomes the leading process. No evidence is found for a significant ABC effect beyond that given by the conventional t-channel $\Delta\Delta$ excitation. This holds also for the double-pionic fusion to the quasibound ^{2}He. The data are compared to model predictions, which are based on both pion and ρ exchange. Total and differential cross sections are at variance with these predictions and call for a profound modification of the ρ-exchange. A phenomenological modification allowing only a small ρ exchange contribution leads to a quantitative description of the data.

Two-pion production in nucleon-nucleon collisions connects $\pi\pi$ dynamics with baryon and baryon-baryon degrees of freedom. In the special case that the participating nucleons fuse to a bound nuclear system, there is the puzzling ABC effect, which stands for a low-mass enhancement in the isoscalar $\pi\pi$ invariant mass spectrum. Very recent experiments on this topic are discussed in terms of a $\Delta\Delta$ mediated isoscalar resonance in the baryon-baryon system as source for this peculiar ABC effect[1,2,3].

By contrast the isovector $\pi\pi$ channel in double-pionic fusion behaves regularly, i.e. shows no ABC effect and follows the expectations from conventional t-channel $\Delta\Delta$ calculations [4]. Also in the two-pion production to unbound nuclear systems the ABC effect was thought to be absent. However, a very recent inclusive measurement of the reaction $pp \to ppX$, where X stands for ejectiles not detected in the experiment, reports evi-

dence for an ABC effect also in this case [5].

A recent isospin decomposition [6] of the total cross sections measured in the reactions $pp \to pp\pi^+\pi^-$, $pp \to pp\pi^0\pi^0$, $pp \to pn\pi^+\pi^0$ and $pp \to nn\pi^+\pi^+$ reveal these two-pion production channels to be dominated by excitation and decay of resonances. In particular the $N^*(1440)$ dominates at energies close to threshold and the $\Delta\Delta$ system and possibly the $\Delta(1600)$ at higher incident energies. The latter is supposed to contribute primarily to the $pp \to nn\pi^+\pi^+$ and also to the $pp \to pn\pi^+\pi^0$ channel.

In view of the challenging interpretation [2] offered for the ABC effect in isoscalar $\pi\pi$ channels in case of double-pionic fusion and the reported evidence in the inclusive $pp \to ppX$ reaction it appears mandatory to study the isoscalar $\pi\pi$ production with exclusive and kinematically complete measurements in the case, where the two participating nucleons do not fuse into a final nuclear bound system. Among the two possible choices, the $pp\pi^+\pi^-$ or the $pp\pi^0\pi^0$ channel, the latter one is especially appealing, since it contains no $\pi\pi$ isovector contributions, only isoscalar and isotensor parts with the isoscalar part being the by far dominating one [6]

From previous work it is known that the $pp \to pp\pi^+\pi^-$ and $pp \to pp\pi^0\pi^0$ reactions in the near-threshold region are well understood as being dominated by excitation and decay of the Roper resonance [7,8,9,10]. At higher energies theoretical calculations [7] predict the t-channel $\Delta\Delta$ excitation to play the dominant part. These calculations are compared in Figs. 1 - 5 with the differential and total cross section data for the $pp \to pp\pi^0\pi^0$ reaction obtained in this work.

Since there have been no exclusive measurements of the $pp \to pp\pi^0\pi^0$ channel in the energy region of interest, we have carried out a systematic program of exclusive two-pion production measurements in pp collisions from threshold up to $T_p = 1.36$ GeV using the WASA detector [11] with the hydrogen pellet target system at the CELSIUS storage ring of the The Svedberg Laboratory in Uppsala. The detector has nearly full angular coverage for the detection of charged particles and photons. The forward detector consists of a thin-walled window plastic scintillator hodoscope at the exit of the scattering chamber, followed by straw tracker, plastic scintillator quirl and range hodoscopes, whereas the central detector comprises an electromagnetic calorimeter consisting of 1012 CsI (Na) crystals, and in its inner part a plastic scintillator barrel surrounding a thin-walled superconducting magnet containing a mini drift chamber for tracking.

Neutral pions are reconstructed from photons detected and identified in the central detector. Protons are detected in the forward detector and identified by the ΔE-E technique. Since the forward detector cone does not cover the full kinematic angular range for protons at high incident energies, the detection efficiency for protons at medium center-of-mass (cms) angles is reduced. This introduces systematic uncertainties in particular in the proton angular distribution. Since due to the identity of the two incident particles, the angular distributions have to be symmetric about 90°, the observed asymmetries about 90° (see Figs. 3 and 4) may hence serve as a measure of such systematic errors in the data. We estimate the systematic uncertainties due to this deficiency of full phase space coverage by using various model calculations in the Monte Carlo simulations of the detector response and acceptance corrections. The estimated systematic uncertainties are shown by dark-shaded histograms in Figs. 2 - 5.

The absolute normalization of the data has been achieved by a simultaneous measurement of elastic scattering and/or single pion production, for which the cross sections are known. Since in particular the single-pion production cross sections are not known better than to an accuracy of 20 %, this uncertainty transmits also to the cross sections deduced for the $pp \to pp\pi^0\pi^0$ reaction. For details of the data analysis see, *e.g.* Refs. [4,6].

Experimental results for the low-energy range $T_p < 1$ GeV have been published [10] in connection with the discussion of the properties of the Roper resonance. In addition close-to-threshold results from previous PROMICE/WASA measurements are given in Ref. [12].

The total cross section data from this work have been published already [6] in connection

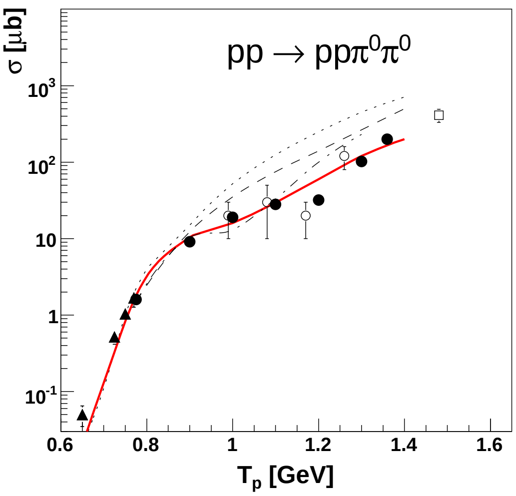

Figure 1. Total cross sections for the $pp \to pp\pi^0\pi^0$ reaction. Data are represented by open (bubble chamber data, Refs. [13,14]) and filled symbols (WASA data, Refs. [6,12]). The dotted lines show the original calculation of Ref. [7]. The dashed, dash-dotted and solid lines are calculations with modifications described in the text.

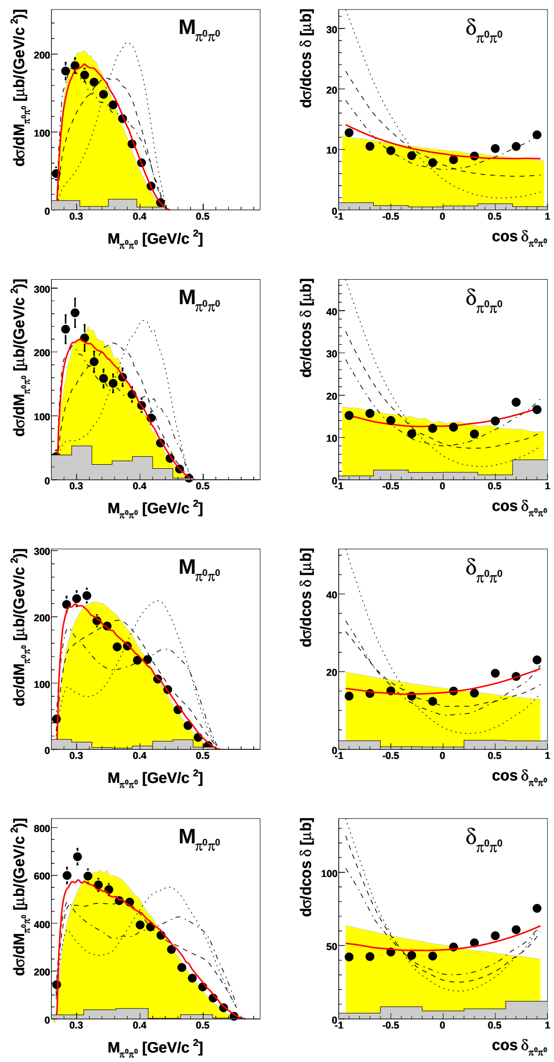

Figure 2. Distribution of the $\pi^0\pi^0$ invariant mass $M_{\pi^0\pi^0}$ (**left**) and the $\pi^0\pi^0$ opening angle $\delta_{\pi^0\pi^0}$ (**right**) for the $pp \to pp\pi^0\pi^0$ reaction at beam energies T_p = 1.0, 1.1, 1.2 and 1.3 GeV (from **top** to **bottom**). Solid dots represent the experimental results of this work. The light-shaded areas denote phase space distributions and dark-shaded histograms systematic uncertainties. The dotted lines show the original calculation of Ref. [7]. The dashed, dash-dotted and solid lines are calculations with modifications described in the text. All calculations are normalized in area to the data.

with the isospin decomposition of two-pion production data. They are shown in Fig. 1 together with previous bubble-chamber results [13, 14]. The total cross section keeps rising from threshold up to $T_p \approx 1$ GeV, where it levels off and proceeds only slowly rising until 1.2 GeV. Thereafter it continues steeply rising until 1.5 GeV, where it finally levels off again – see Fig. 3 in Ref. [6]. As has been demonstrated [6], the low-energy structure is due to the Roper resonance, whereas the renewed rise at higher energies can be associated with the dominance of the $\Delta\Delta$ excitation.

In Figs. 2 - 5 we exhibit a selection of eight distributions, which are most significant with regard to their physics content. Note that for a four-body reaction with unpolarized beam and target there are seven independent single differential distributions. For T_p = 1.0, 1.1, 1.2 and

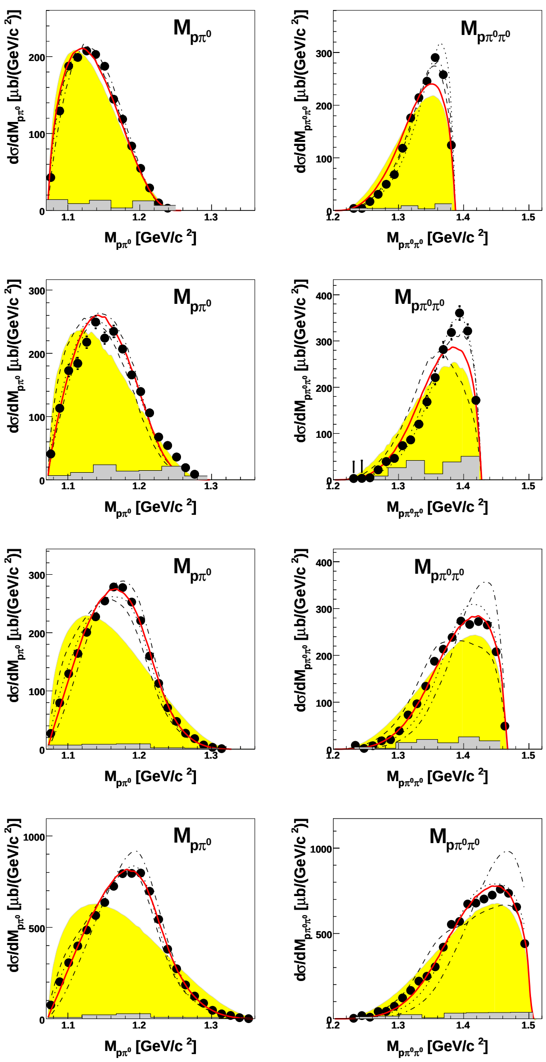

Figure 3. Same as Fig. 2 but for the distributions of the invariant masses $M_{p\pi^0}$ (**left**) and the $M_{pp\pi^0}$ (**right**) for the $pp \to pp\pi^0\pi^0$ reaction at beam energies T_p = 1.0, 1.1, 1.2 and 1.3 GeV (from **top** to **bottom**).

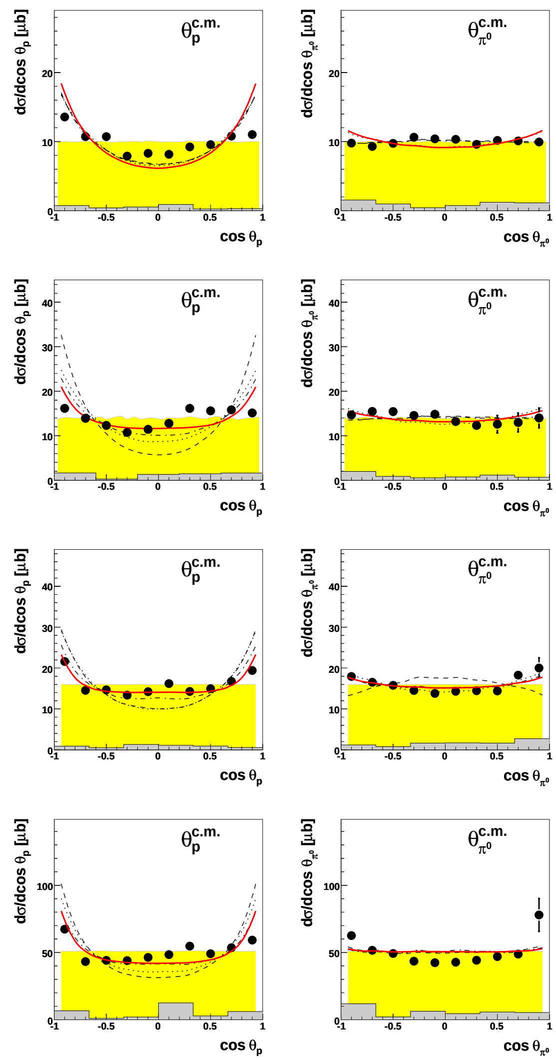

Figure 4. Same as Fig. 2 but for the distributions of the cms angles Θ_p (**left**) and the Θ_{π^0} (**right**) for the $pp \to pp\pi^0\pi^0$ reaction at beam energies T_p = 1.0, 1.1, 1.2 and 1.3 GeV (from **top** to **bottom**).

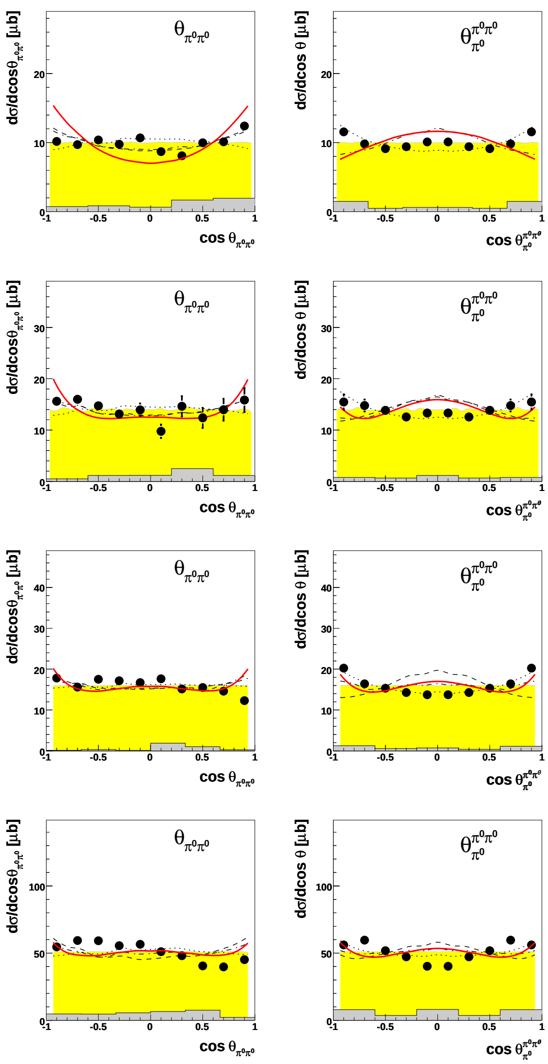

Figure 5. Same as Fig. 2 but for the distributions of the angle of the $\pi^0\pi^0$ system in the cms $\Theta_{\pi^0\pi^0}$ (**left**) and the π^0 angle in the $\pi^0\pi^0$ subsystem $\Theta_{\pi^0}^{\pi^0\pi^0}$ (**right**) for the $pp \to pp\pi^0\pi^0$ reaction at beam energies T_p = 1.0, 1.1, 1.2 and 1.3 GeV (from **top** to **bottom**).

1.3 GeV differential distributions are shown for the invariant masses $M_{\pi^0\pi^0}$, $M_{p\pi^0}$, $M_{pp\pi^0}$, the opening angle between the two pions $\delta_{\pi^0\pi^0}$, the proton angle Θ_p, the π^0 angle Θ_{π^0}, the angle of the $\pi^0\pi^0$ system $\Theta_{\pi^0\pi^0}$ - all in the cms - as well as the π^0 angle in the $\pi^0\pi^0$ subsystem (Jackson frame).

In Figs. 1 - 5 the data are compared to pure phase space distributions (light-shaded areas in Figs. 2 - 7) as well as to calculations of Ref. [7] with and without modifications as will be discussed in the following. As a convention we show all theoretical model distributions normalized to the experimental total cross section, *i.e.* to the same area in the differential distributions. This is because we are interested here in the shape of the differential distributions. The comparison with the absolute total cross sections is done in Fig. 1.

We see that many of the experimental differential distributions are not far from the phase space distributions. With regard to angular distributions significant deviations from isotropy are observed only for the Θ_p and $\delta_{\pi^0\pi^0}$ distributions. The first one is largely characterized by the t-channel exchange as demonstrated in Ref. [8], whereas the latter one is strongly correlated with the $M_{\pi^0\pi^0}$ spectrum as discussed in some detail in Ref. [9]. In fact, we observe some deviations from phase space also for the $M_{\pi^0\pi^0}$ spectrum as will be discussed below. However, really large deviations from phase space are observed in spectra, which are correlated with Δ excitation: $M_{p\pi^0}$, $M_{p\pi^0\pi^0}$ and $M_{pp\pi^0}$. The peaks in all these invariant mass spectra build up increasingly with increasing energy and reflect the increasing excitation of the $\Delta\Delta$ system, the resonance pole of which is reached at $T_p \approx 1.3$ GeV, i.e. the highest energy considered in this work. The M_{pp} spectrum, a sample of which is shown in part in Fig. 6, is kinematically complementary to the $M_{\pi^0\pi^0}$ spectrum.

Next we confront the data with model predictions [7] of the Valencia group and subsequent modifications of the original calculations. The dotted lines in Figs. 1 - 5 show the original predictions, which though renormalized in area give huge deviations from the measured distributions - in particular in the $M_{\pi^0\pi^0}$ and $\delta_{\pi^0\pi^0}$ spectra. For

the $M_{\pi^0\pi^0}$ spectrum these calculations predict a kind of double-hump structure with a large enhancement at high invariant masses, which is absent in the data. With regard to the $\pi^0\pi^0$ opening angle $\delta_{\pi^0\pi^0}$ these calculations predict a preferential antiparallel emission of the two pions, which again is not supported by the data.

The predicted double-hump structure is reminiscent of similar predictions for the ABC effect in the double-pionic fusion. There a double-hump structure has been predicted [15,16,17] based on a t-channel $\Delta\Delta$ excitation — with some of such calculations [18,19] emphasizing a particular strong high-mass enhancement. By contrast exclusive and kinematically complete measurements of the isoscalar double-pionic fusion find only a huge low-mass enhancement, but no or no significant high-mass enhancement [1,2,20]. As already mentioned above our data for the $M_{\pi^0\pi^0}$ spectrum are in qualitative agreement with phase space, i.e. we observe neither a spectacular low-mass enhancement (ABC effect) nor a spectacular high-mass enhancement.

In order to shed some light into the failure of the theoretical predictions, we readjust these calculations step by step first by implementing the knowledge accumulated from the studies of the near-threshold region (T_p < 1 GeV), which is governed by excitation and decay of the Roper resonance. From the analysis of the data at T_p = 0.775 and 0.895 GeV [10] we obtain a value for the relative branching between the decay via the Δ resonance, *i.e.* $N^* \to \Delta\pi \to N(\pi\pi)_{I=l=0}$ and the direct decay $N^* \to N(\pi\pi)_{I=l=0}$, which is four times smaller than that quoted in PDG [21] and used in Ref. [7], but in agreement with a recent analysis of data on pion- and photo-induced pion production on the nucleon [22]. Updating the model calculations with this new branching for the Roper decay (dashed lines in Figs. 1 - 5) leads not only to a quantitative description of the data for T_p < 1 GeV [10], but also to a considerable improvement in the description for $T_p \geq 1$ GeV, though there are still substantial deficiencies in the $M_{\pi^0\pi^0}$ and $\delta_{\pi^0\pi^0}$ distributions.

Next we readjust the total strength of the Roper excitation. We know from the isospin decomposition [6] of the total two-pion production cross sections that for $T_p \geq 1$ GeV the excitation of the Roper resonance comes out much too strong in the Valencia model calculations: Hence we readjust the strength of the Roper excitation according to the isospin decomposition result. That way we force the calculations to also reproduce the total cross sections. The outcome of this modified calculation is shown in Figs. 1 - 5 by the dash-dotted lines. We now get a good description of the data at T_p = 1.0 GeV. However, deviations from the data still increase with increasing beam energy. In particular, because the last modification increased strongly the dominance of $\Delta\Delta$ excitation for T_p > 1 GeV, we obtain pronounced double-hump and parabolic structures, respectively, in the $M_{\pi^0\pi^0}$ and $\delta_{\pi^0\pi^0}$ distributions.

Since these failures are now intimately connected to the treatment of the $\Delta\Delta$ excitation, further improvements have to be sought in a modification of this process. As demonstrated already in Ref. [9], double-hump structures in $M_{\pi^0\pi^0}$ spectra are generated by a $\vec{k_1} \cdot \vec{k_2}$ term, where $\vec{k_1}$and $\vec{k_2}$ denote the 3-momenta of the two emitted pions. In the description of the $\Delta\Delta$ process we find indeed such a $\vec{k_1} \cdot \vec{k_2}$ term associated with the ρ exchange, see equation (A.10) in Ref. [7]. A closer inspection of eq. (A.10) shows the following problem: the ρ exchange provides isotropic angular distributions for pions as required by the data, however, provides also a $\vec{k_1} \cdot \vec{k_2}$ term at variance with the data. On the contrary, the pion exchange contains no $\vec{k_1} \cdot \vec{k_2}$ term, but involves a strong angular dependence for the pions - in disagreement with the data. Whereas pion-exchange appears to be straightforward theoretically and well established in the description of pion-production processes, stringent tests are missing for the ρ-exchange. Also since the ρ-exchange part in the t-channel $\Delta\Delta$ description of Ref. [7] is the by far dominating part, we have to seek for a solution in the ansatz for the ρ exchange.

In a recent theoretical work on two-pion production Cao, Zou and Xu [23] find that, in contrast to Ref. [7], ρ-exchange is small compared to pion-exchange. Triggered by this finding and in

view of our problems to describe the data within the context of the ansatz equation (A.10) in Ref.[7], we investigated the possibility to achieve a reasonable description of the data by varying the coupling strength of ρ exchange. For simplification, compared to eq. (22) of Ref.[7], we use the longitudinal and transversal exchange contributions to be given purely by π- and ρ-exchange, respectively. Also for sake of simplicity we drop the monopole meson form factors.

In order to have the description relativistically more appropriate we take the momenta of the pions from the Δ decay in the corresponding Δ systems and correct them by the Blatt-Weisskopf barrier factors as given by Pilkuhn [24] and used also in Refs. [15,23]. These relativistic corrections are, of course, negligible close to threshold, but lead to sizable and significant changes at higher energies. In particular the calculated total cross sections no longer keep steeply rising beyond the resonance pole as in Ref. [7], but go into saturation as shown in Ref. [23]. The latter behavior agrees with the trend of data at high energies.

In fact, we find a quite reasonable description of the data by reducing the coupling strength of the ρ exchange (A.10) of Ref.[7] by an order of magnitude. The solid lines in Figs. 1 - 5 show our calculations with the ρ coupling strength reduced by a factor of 12 and reversed in sign. Note that now the ρ-exchange is only a small correction to the leading π-exchange, but this correction leads still to a sizable improvement in the description of the differential data. The description of the data is still far from being perfect, but at least all major features of the data are reproduced.

Fig. 1 shows the energy dependence of the total cross section of the $pp \to pp\pi^0\pi^0$ reaction. As mentioned in the introduction the striking feature is the slow rise of the cross section between $T_p =$ 1.0 and 1.2 GeV, which is reproduced neither by the calculations of Ref. [7] nor by the more recent ones of Ref.[23]. The primary reason for that failure is that in both calculations the Roper excitation keeps rising beyond $T_p = 1.0$ GeV, which is at variance with the finding from the isospin decomposition [6]. As pointed out above the differential cross sections require the Roper excitation to be cut down, too, in accordance with the isospin decomposition result. Hence, accounting for the latter and using the modified $\Delta\Delta$ description we succeed in obtaining a description for the total cross section, which is in quantitative agreement with the data.

The comparison to the data shows that the ρ exchange contribution as treated in Ref. [7,18] needs substantial modification. This is true both for the two-pion production to unbound nuclear systems and for the double-pionic fusion. No significant high-mass enhancement is observed in either case, which would be a signature of a dominant ρ-exchange.

In the double-pionic fusion experiments a huge low-mass enhancement (ABC-effect) is found instead, which has been associated with the formation of an isoscalar resonance via a $\Delta\Delta$ doorway [2]. Such an isoscalar resonance can not contribute to the isovector $pp \to pp\pi^0\pi^0$ channel discussed here. The small low-mass enhancement visible in the data can be fully associated with the conventional t-channel $\Delta\Delta$ excitation.

In Ref. [5] the appealing idea has been put forward that though there is no bound state in the isovector NN system one could look for a quasibound ^{2}He double-pionic fusion process in the reaction $pp \to pp\pi\pi$ by requiring that the emitted protons have very small kinetic relative energies. In Ref. [5], which presents and discusses COSY-ANKE data for the inclusive reaction $pp \to ppX$, this requirement was achieved by the condition $M_{pp} \leq 2m_p + 3$ MeV. These data — covering just the forward angle region — exhibit a pronounced low-mass enhancement in the pp missing mass spectrum, which is equivalent to the associated $\pi\pi$ invariant spectrum. In our experiment we cover practically the full phase space of the two-pion production reactions. Though we have accumulated quite some statistics of events distributed over the full phase space, we lose nearly all events, if we apply the above M_{pp} cut. Therefore, in order to have acceptable statistics, we relax the above constraint to $M_{pp} \leq 2m_p + 10$ MeV. In Fig. 6 we show for $T_p = 1.3$ GeV — the energy, where the $\Delta\Delta$ process is most obvious in our data — the M_{pp} spectrum together with the indicated cut as well as the $M_{\pi^0\pi^0}$, $M_{p\pi^0}$ and $\Theta_{\pi^0\pi^0}$ spectra

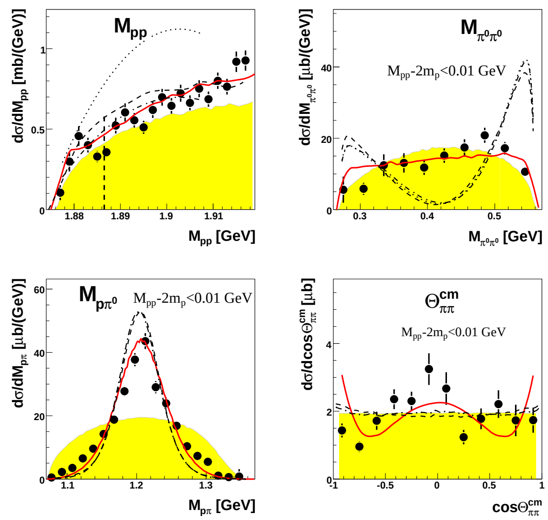

Figure 6. Differential distributions at $T_p = 1.3$ GeV for the ^{2}He scenario. **Top left**: M_{pp} spectrum for the full phase space (only low-mass part shown). The distributions for $M_{\pi^0\pi^0}$ (**top right**), $M_{p\pi^0}$ (**bottom left**) and $\Theta_{\pi^0\pi^0}$ (**bottom right**) are plotted with the ^{2}He condition $M_{pp} < 2m_p + 10$ MeV (vertical line in the M_{pp} spectrum). The drawn lines represent calculations as described in the caption of Fig. 2 and text. The shaded areas show the phase space distributions.

resulting from this cut. In the M_{pp} spectrum we observe an indication of the low-mass enhancement produced by the pp final-state interaction, which is also included in the theoretical calculations. In order to focus on small masses we plot this spectrum only in the low-mass range in Fig. 6. We see that the cut $M_{pp} \leq 2m_p + 10$ MeV is still within the region dominated by the pp final-state interaction ensuring thus relative s-waves between the two protons. Within the limited statistics the data in the constrained $M_{\pi^0\pi^0}$ spectrum exhibit some high-mass enhancement as expected from the pioneering work of Risser and Shuster [15] concerning the production of an isoscalar pion pair via the $\Delta\Delta$ excitation in the double-pionic fusion. The constrained $M_{p\pi^0}$ spectrum exhibits the Δ peak ensuring the $\Delta\Delta$ process to be the dominating process in the ^{2}He case, too.

The solid lines, which present the modified theoretical description of the $pp \to pp\pi^0\pi^0$ reaction, give a reasonable description for this constrained phase space scenario. On the contrary, the broken lines exhibit a very pronounced double-hump structure in the $M_{\pi^0\pi^0}$ spectrum due to the dominance of the ρ-exchange in these calculations. This behavior is clearly at variance with the data. On basis of the model calculation we also ensure that the change in the cut from a 3 MeV to a 10 MeV range does not change the results qualitatively. The $\Theta_{\pi\pi}^{cm}$ angular distribution points to some sizable d-wave contribution, which is in support of the respective ansatz in Ref. [5]. The increased d-wave contribution as compared to the results for the full $pp \to pp\pi^0\pi^0$ reaction is not unexpected, since the ^{2}He cut forces the two emerging protons to be in relative s-wave. The decay of the two excited Δ states results in a double p-wave emission of the two pions. This in turn leads to s- and d-waves in the emitted $pp\pi^0\pi^0$ system.

Finally we compare our calculations to the COSY-ANKE data in Fig. 7 by restricting the calculations further to the angular range covered by the ANKE experiment, which is $cos\Theta_{pp} > 0.95$ with $\Theta_{pp} = 180° - \Theta_{\pi^0\pi^0}$ and $\Theta_p^{lab} \leq 12°$. We again obtain an essentially quantitative agreement with the data at $T_p = 1.1$ and 1.4 GeV using the modified model description, whereas the ρ-exchange dominated calculations again give a double-hump structure in vast disagreement with the data.

Summarizing, we have presented first exclusive and kinematically complete measurements of the $\Delta\Delta$ system excited in the $pp \to pp\pi^0\pi^0$ reaction. The data are well described by a conventional t-channel $\Delta\Delta$ calculation, where the ρ exchange contribution is strongly reduced compared to that in Ref. [7]. The same holds for the subset of data, which corresponds to the double-pionic fusion to a quasibound ^{2}He nucleus. No evidence is found for a significant low-mass enhancement

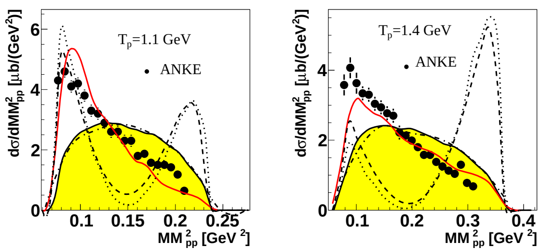

Figure 7. $M_{\pi^0\pi^0}$ spectra at $T_p = 1.1$ and 1.4 GeV for the ^{2}He condition $M_{pp} < 2m_p$+3 MeV and the ANKE angular constraints $cos\Theta_{pp} > 0.95$ with $\Theta_{pp} = 180^\circ - \Theta_{\pi^0\pi^0}$ and $\Theta_p^{lab} \leq 12^\circ$. The solid dots represent the ANKE data [5] and the drawn lines calculations as described in the caption of Fig. 2 and text. The shaded areas show the phase space distributions.

in the $M_{pi^0\pi^0}$ spectra (ABC effect) beyond that given by the conventional t-channel $\Delta\Delta$ excitation process. The new data sets should serve as a significant test case for theoretical treatments of multipion production.

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